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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

Satellite Data Requirements of Atlantic Oceanographic and Meteorological Laboratories for Studies of Ocean Physics and Solid Earth

BOULDER, COLO.
SEPTEMBER 1971

U.S. DEPARTMENT OF COMMERCE
Peter G. Peterson, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

ENVIRONMENTAL RESEARCH LABORATORIES
Wilmot N. Hess, Director

NOAA TECHNICAL REPORT ERL 225-AOML 5

Satellite Data Requirements of Atlantic Oceanographic and Meteorological Laboratories for Studies of Ocean Physics and Solid Earth

INVESTIGATORS:

GEORGE MAUL	Physical Oceanographic Laboratory
BERNARD ZETLER	Physical Oceanographic Laboratory
DONALD HANSEN	Physical Oceanographic Laboratory
KIRBY HANSON	Sea-Air Interaction Laboratory
DUNCAN ROSS	Sea-Air Interaction Laboratory
GEORGE KELLER	Marine Geology and Geophysics Laboratory
JOHN APEL	Office of the Director

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September 1971

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SUMMARY OF REQUIREMENTS

This document has been prepared by research scientists at the Atlantic Oceanographic and Meteorological Laboratories in response to the memorandum from the Associate Administrator of NOAA requesting NOAA Laboratory "Requirements for Ocean Physics and Solid Earth Data."

These Laboratories are broad based and interdisciplinary covering solid earth, oceanography, and meteorology. Although the requirements for meteorology are not included here, the range of requirements for application to ocean physics and solid earth is large. Table 1 shows that the investigators are asking for sensors covering a large range of the electromagnetic spectrum, from reflected solar radiation in the visible spectrum to both active and passive microwave systems. These measurements will provide data that can be used to describe the state, physical properties, and energetics of the surface and near-surface layer of all of the world's oceans.

Table 1. *Summary of Data Applications Related to the Electromagnetic Spectrum*

Spectrum	Date Application
Visible	Ocean Turbidity Detection Shoreline Topography Bottom Topography
Broadband Solar Broadband IR	Ocean/Atmosphere Energetics
IR "Window"	Ocean Currents Eckman Divergence and Wind Stress Long-Term, Sea-Air Interaction Teleconnections of World Oceans
Active Microwave	Sea State Tides Ocean Slopes
Passive Microwave	Salinity Surface Wind Waves

The programs that are envisioned to carry out these studies are listed in table 2; the purpose and the main investigator(s) are also included.

The sensor or measurement requirements are listed in table 3 together with categories for orbit, resolution, and accuracy desired. The ideas contained here have not been constrained to fit any particular satellite, orbit, or sensor system; however, there were some obvious matches of plans and requirements.

Some of the values in table 3 have been difficult to specify for several reasons. This means that although a single value (in some cases) has been given, it is simply the investigators "reasonable, first estimate" at the value based on his knowledge at this time. Obviously, some values should be adjusted as new information becomes available. Therefore, it would be desirable for those who may make use of table 3 in developing satellite systems to have further discussion with these investigators.

Table 2. Proposed Programs for Studies of Ocean Physics and Solid Earth

Purpose	Investigator
Global Ocean Radiation Budget	
Determine Radiative Heat Sources and Sinks for World Oceans	Dr. K. Hanson
Global Ocean Sea Surface Temperature	
Study Eckman Divergence Related to Surface Wind Stress Diagnostic Studies of Long-Term Sea-Air Interaction Phenomena Study Large Scale Teleconnections Between World's Oceans	Dr. K. Hanson
Water Mass Identification	
Bioassay Current Boundaries and Advection of Pollutants Applications to Marine Transportation Estuarine Studies	Mr. G. Maul
Surface Wind and Wave Conditions	
Prediction of Surge Associated with Storms and Hurricanes Studies Leading to Improved Operational Forecasting of Ocean Surface Winds, Wave, Surf Conditions, and Storm Surge	Mr. D. Ross
Sea State Determination	
Research on Forecasting Techniques	Dr. J. Apel Mr. B. Zetler
Tidal Amplitudes	
Worldwide Tide Forecasting	Mr. B. Zetler Dr. J. Apel
Ocean Slopes Over (a) Currents and (b) Deep Trenches	
Global Ocean Circulation	Dr. J. Apel Dr. D. Hansen
Gravity Anomalies	Mr. B. Zetler
Changes in Shoreline and Seafloor Features due to Storms	
Research on Storm Effects of Shoreline and Shallow Water Features	
Turbid Water Mass Movement	
Concentration, Composition, and Transport	Dr. G. Keller

Table 3. Data Requirements for Studies of Ocean Physics and Solid Earth

Sensor or Measurement Requirements	Orbit: Inclination (deg)	Orbit: Altitude or Period (km)	Orbit: Approx. Local Sun Time	Resolution: Time	Resolution: Space (km)	Geophysical: Accuracy	Geophysical: Precision
Program: Global Ocean Radiation Budget							
(a) Solar Radiance, 0.3-3.0μm	81 retro	1100-1500	1200 & 1430	2/day (daylight hr)	100	0.006*	0.003*
(b) IR Radiance, 3-50μm	81 retro	1100-1500	0000 & 1200	2/day	100	0.006*	0.003*
(c) IR Window, 10.5-12.5μm	81 retro	1100-1500	0000 & 1200	2/day	100	1 °K	0.5 °K
(d) Total Water Vapor	81 retro	1100-1500	0000 & 1200	2/day	100	0.2 cm	---
Program: Global Ocean Sea Surface Temperature							
Sea Surface Temperature (10.5-12.5μm)	81 retro	1100-1500	0000	1/day	100	1 °K	0.5 °K
Program: Water Mass Identification							
(a) Sea Surface Temperature HRIR (10.5-12.5μm)	81 retro	1100-1500	0930 or 1430	1/day	2	1 °K	0.5 °K
(b) Salinity, 1.4 GHz	81 retro	1100-1500	0930 or 1430	1/day	2	1(°/oo)	0.5 °K
(c) Ocean Turbidity, 0.46μm and 0.54μm (0.015μm spectral interval)	81 retro	1100-1500	0930 or 1430	1/day	2	3.0†	1.5†
Program: Surface Wind and Wave Conditions							
Multifrequency Microwave Radiometer 1-3, 5-8, 10, 15-19 GHz dual polarization.	81 retro	(Unspecified, depends on antenna)	0000, 0600, 1200 & 1800	4/day	20-100	Wind: 2 mps Waves: 0.5 m	Wind: 1 mps Waves: 0.5 m
Program: Sea State Determination							
Short-pulse Radar Altimeter, 10 GHz (3 ns pulse, power 2 kW)	∿65	300-400	(see text)	1 look/12 sec over ocean, not continuous meas	4-8	0.5 m	0.5 m
Program: Tidal Amplitudes							
Precision Altimeter with radar/laser altimeter, plus vertical stabilization to 1°.	∿65	300-400	(see text)	100/yr over 20 1° squares (to be specified)	4-8	5 m	1.0 m
Program: Ocean Slopes Over (a) Currents and (b) Deep Trenches							
Precision Altimeter with radar/laser altimeter, plus vertical stabilization to 1°	∿65	300-400	(see text)	(a) 1 obsr/3 days over Gulf Stream (b) 100 obsr/trench for each major ocean trench	4-8	5 m	0.1 m
Program: Changes in Shoreline and Seaflow Features Due to Storms							
Multispectral Radiance 0.46μm, 0.54μm and 0.70μm (with 0.015μm spectral interval)	81 retro	(unspecified)	∿0930 or 1430	1 obsr/15 days	20 m	3.0†	1.5†
Program: Turbid Water Mass Movement							
Multispectral Radiance 0.46μm, 0.54μm and 0.70μm (with 0.015μm spectral interval)	81 retro	(unspecified)	∿0930 or 1430	1 obser/15 days	20 m	3.0†	1.5†

*cal cm^{-2} min^{-1} †W m^{-2} $ster^{-1}$ μm^{-1}

PART I: OCEAN PHYSICS PROGRAMS

1. GLOBAL OCEAN RADIATION BUDGET

Kirby Hanson

1.1 Background

The global radiation budget at the earth's surface has been calculated by a number of investigators including Kimball (1928) as early as 1928. More recently, Budyko (1955, 1963), Black (1956), Ashbel (1961), and Wyrtki (1965) have made similar determinations. On comparing observed irradiance values in the tropical Pacific with values calculated by the investigators mentioned above, Quinn and Burt (1968) found the calculations were 15 to 27 percent too low at Canton Island and 15 to 18 percent too low at Wake Island.

From irradiance measurements in the Line Islands (near the equator, south of Hawaii), Cox and Hastenrath (1970) stated that the "downward-directed short-wave radiation at Palmyra is considerably larger than expected from available climatic mean maps. The climatic mean irradiance values were calculated from cloud observations and empirical relationships of irradiance as a function of cloudiness (Black, 1956; Bernhardt and Phillipps, 1958; and Budyko, 1963)."

At Swan Island in the Caribbean, this author found that calculated values of the solar irradiance by Ashbel (1961) and Budyko (1963) are 3 to 9 percent too low.

These scattered observations in the tropics are consistent, because they show more solar energy reaching and being absorbed in the tropical oceans than was previously thought. This recent finding is also consistent with satellite observations of the earth's radiation budget; these show that about 30 percent more solar radiation is absorbed by the earth-atmosphere system in the tropics than suggested by pre-satellite calculations (House, 1965; Vonder Haar, 1968; London and Sasamori, 1971; and Vonder Haar and Hanson, 1969).

From these surface and satellite observations, it now appears that the tropical oceans are receiving perhaps 10 to 20 percent more solar energy than is suggested by the climatic mean maps that have been published in the last 10 years.

Satellite measurements of the reflected solar irradiance leaving the atmosphere are now wrong by only a few percent, when averaged over seasonal and annual time scales. However, the error of *surface* irradiance calculations (based on cloud observations) on the same time scale is about an order of magnitude larger.

We propose to develop parameterization techniques based on satellite observed broadband solar irradiance, to apply these techniques to satellite data, and to determine the global ocean radiation budget over monthly, seasonal, and annual time scales. We also propose to do a similar parameterization for the IR irradiance at the earth's surface based on satellite observed IR radiance.

1.2 Requirements

The satellite data requirements for this section are specified in table 3. They are:

1. Upwelling broadband solar radiance (0.3 to 3 μm)
   - complete global coverage at least two per day during *daylight* hours: one pass at local noon and one at 1430 UT/LT
   - horizontal resolution of 100 km
   - accuracy of 2 percent, or 0.006 cal cm^{-2} per min
   - precision of 1 percent, or 0.003 cal cm^{-2} per min.
2. Upwelling broadband IR radiance (3 to 50 μm)
   - complete global coverage at least two per day: one pass at local noon and one at midnight
   - horizontal resolution of 100 km
   - accuracy of 2 percent, or 0.006 cal cm^{-2} per min
   - precision of 1 percent, or 0.003 cal cm^{-2} per min.

3. Upwelling IR window radiance (10.5 - 12.5 μm)

   - complete global coverage at least two per day: one pass at local noon and one at midnight
   - horizontal resolution of 100 km
   - accuracy of 1°C (effective radiation temperature).

4. Total precipitable water vapor (cm)

   - complete global coverage at least two per day: one pass at local noon and one at midnight
   - horizontal resolution of 100 km
   - accuracy 0.2 cm.

Requirement 4 will be limited by clouds in the sensor's field of view. In those cases, a statistical estimate with higher resolution sensors (<100 km) should be made to determine clear sky total precipitable water.

Two observations of the upwelling broadband solar radiance are required during daylight. The hours suggested are 1200 and 1430 LST (local sun time). Polar orbitters are assumed at these hours.

The IR radiance, IR window, and total water vapor measurements are required at 0000 and 1200 LST. Thus, one polar orbitter is required.

2. GLOBAL OCEAN SEA-SURFACE TEMPERATURE

Kirby Hanson

2.1 Background

The "southern oscillation," a long-term sea-air interaction phenomenon, was first described by Sir Gilbert Walker in 1924. Following this, it received little attention until the 1960's when Austin (1960) examined mid-Pacific equatorial ocean temperatures, and Bjerknes (1966) suggested the importance of this tropical sea-air interaction phenomenon to the predictability of the atmosphere in midlatitudes. Berlage (1966) has studied this phenomenon in relation to world weather for nearly 40 years.

The Eastern Pacific Ocean is the largest area of subnormal temperatures observed anywhere in tropical oceans. As stated by Bjerknes (1969):

> "The cause of the temperature deficiency is partly the cold water supplied by the Humbolt Current from southern sources, aided by upwelling along the Chilean and Peruvian coast. Even more important, though, is the upwelling along 10,000 km, more or less, of the Pacific equator.
>
> "The upwelling in the open ocean along the equator is due to the prevailing easterly winds. In addition to the westward drift produced by these winds, a diverging Ekman drift is maintained, to the right north of the equator and to the left south of the equator, so as to pump upwelling water to the surface at the equator. As long as this process continues uninterruptedly, more and more upwelling water gathers at the surface and spreads sideways from the equator until a tongue of cold water establishes as wide as shown in figure 1."

Ocean temperature anomalies in this cold current can also lead to catastrophic conditions for some South American countries. The *El Niño* is an anomalously *warm* ocean temperature condition that occurs in the otherwise cold water along the west coast of South America. The occurrence of it and associated meteorological conditions can lead to torrential rains and flooding in the normally arid regions of Ecuador and Peru; red tide; invasion by tropical nekton; and mass mortality of various marine organisms including guano birds, sometimes with subsequent decomposition and release of hydrogen sulfide (Wooster, 1960) (cited by Quinn, 1970).

Ocean temperature anomalies also have a large effect on precipitation along the equatorial dry zone of the Pacific. A time plot of sea/air temperatures and precipitation at Canton Island (Bjerknes, 1969) is shown in figure 2. Many

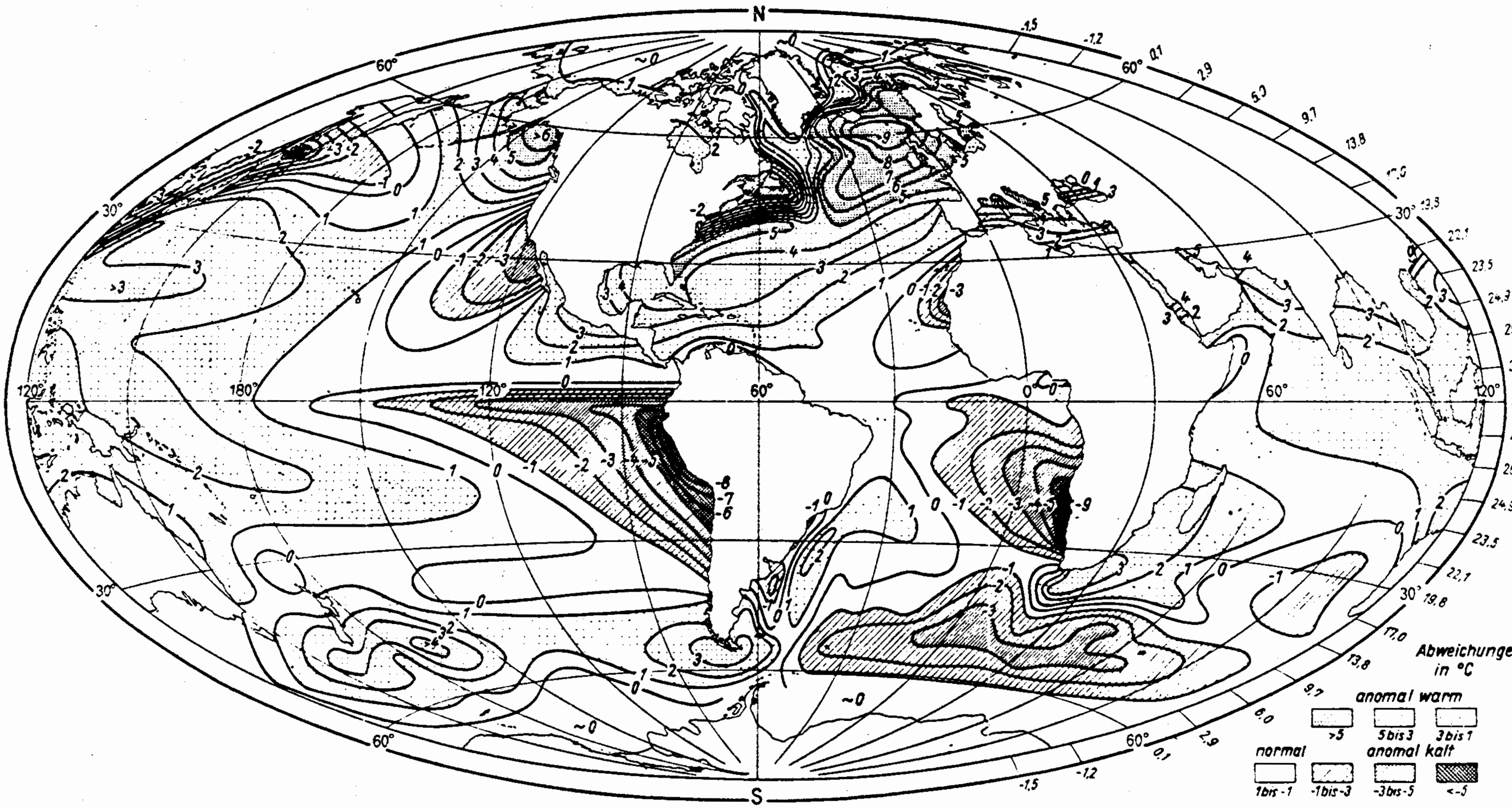

Figure 1. Sea-surface temperature represented as deviation from the average at each latitude (after Bjerknes, 1969; from Dietrich and Kalle, 1957).

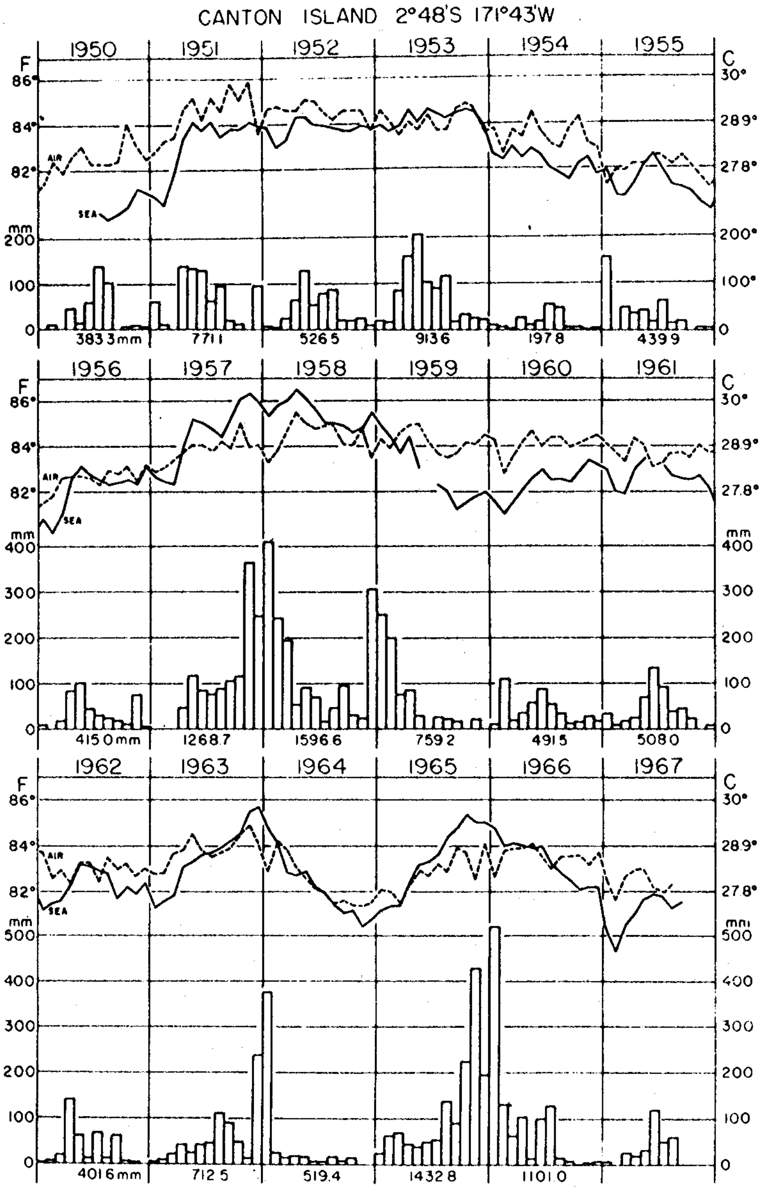

Figure 2. Time series of monthly air and sea temperatures and of monthly precipitation at Canton Island from 1950 to 1967 (from Bjerknes, 1969).

other investigators have examined this response of the tropical atmosphere (more precipitation) to warm surface waters and its self-amplification (Krueger and Gray, 1969; Quinn, 1970; and others). This increased precipitation has been suggested as an explanation for the midlatitude westerlies being stronger during periods of warm surface temperatures in the equatorial dry zone. The suggestion is that the greater heat supply from the equatorial ocean is added to the atmospheric Hadley circulation by precipitation intensifying that circulation and producing more than the normal flux of angular momentum at the midlatitude belt of westerlies (Bjerknes, 1969).

The response of midlatitude circulation patterns to tropical (or extratropical) ocean temperature anomalies has obvious importance to the predictability of the atmosphere. Thus, the initial work by Berlage and Bjerknes has brought on a number of diagnostic studies during the past few years on teleconnections of the atmosphere and ocean (Krueger and Gray, 1969; Namias, 1969). These studies are very useful in establishing the global nature of this phenomena. Furthermore, they have shown the need for global satellite measurements to study these long-term, sea-air interaction phenomena.

Studies that should be undertaken when adequate satellite data are available are:

1. The Ekman divergence has been postulated as a response to the strength of the equatorial trade winds. The time development of sea surface temperature patterns in response to surface wind stress should be studied to verify this or offer another explanation.
2. The long-term sea surface temperature anomalies recorded at Canton Island need to be extended to all of the tropical and subtropical oceans. Unfortunately, only a few island stations record sea surface temperatures, and ships provide only limited data (time and space). Satellite sea surface temperature measurements (to required precision) are required on a global scale to provide the necessary sampling resolution and accuracy to study these anomalies. These will provide basic information for diagnostic studies of long-term sea surface temperature anomalies as a means for forcing (and interacting with) the circulation patterns in the atmophere.
3. If there are large-scale teleconnections between the ocean and atmosphere, we can also expect to have large-scale teleconnections between the world's oceans (with the atmosphere as a link). Sea surface temperature data obtained by satellite will provide basic input for such studies.

2.2 Requirements

The requirement is for sea surface temperature, once a day at 0000 LST, a spatial resolution of 100 km, an accuracy of 1°K, and a precision of 0.5°K.

The satellite measurements required have not been specified in table 3 (only sea surface temperature has been specified). It is assumed that some organization with satellite data processing capability (such as NESS) will reduce the necessary measurements to sea surface temperature values. This requires eliminating the effect of the atmosphere and clouds on the measurement.

3. WATER MASS IDENTIFICATION

George Maul

Oceanic circulation is a fundamental geophysical phenomenon that affects every milligram of biota on this planet. The advection of heat and nutrients is the controlling influence in the primary biological production and hence the entire food web. Major weather systems, such as subtropical cyclones, are influenced (if not controlled) by the ability of the ocean to release thermal energy; regional climates are established because of this. Marine transportation, commercial fishing, deep-sea mining and drilling, national defense, and other such ocean-oriented activities of man are influenced by the surface and near-surface circulation.

If we are to use the ocean in an ecologically acceptable and commercially practical manner, the perturbations in the average surface flow are the meaningful properties that must be measured and eventually predicted. Fortunately, due to the intense baroclinicity of the important currents, there are several surface features that hold promise for detection by remote sensors.

Characteristically, the surface manifestation of major currents, such as the Gulf Stream, Kuroshio, Agulhas, Peru, and Somali, are (1) a high temperature gradient, (2) a high salinity gradient, (3) a high turbidity gradient, (4) a high velocity gradient, (5) a change in sea state, (6) a change in cloudiness or cloud patterns, and (7) a change in sea-surface slope. The possibility of remotely sensing these features and the requirements to do so are discussed in the following paragraphs. The goal is to make appropriate measurements of each of these features and by machine processing and decision, provide the maritime community with synoptic maps. The feasibility of machine processing and decision of multispectral scanner data has been demonstrated by Higer et al. (1970).

3.1 Thermal Gradient Detection

The surface thermal signature of the Gulf Stream has been documented as a reliable, year round, indication of the current (Hansen and Maul, 1970). Attempts to track routinely the thermal boundary by using Nimbus II data have led to the conclusion that the uncontaminated sea surface temperature must be known to ±1°K (Maul, 1972). To accomplish this, we recommend that a high resolution infrared sensor (HRIR), response-limited to the range of oceanic surface temperatures with allowance for atmospheric attenuation (namely 260°K - 310°K), be flown. The subsatellite ground resolution should be about 2 km for meaningful location of the thermal field with respect to the velocity field, the attitude control requirements of the altimeter (discussed in sections 2.4 and 2.5) must keep the location of the HRIR ground spot in an area less than the spot size itself. A second channel that simultaneously measures the planetary albedo with the same resolution is required for cloud detection. The spectral range of the HRIR desired is 10.5 to 12.5 μ, because energy at earth temperatures is maximized, reflected energy is negligible, and atmospheric attenuation due to H_2O, CO_2, and O_3 is small. The albedo channel specifications are less well-determined; however, 0.4 to 0.7 μ should be adequate. The multispectral approach (Anding and Kauth, 1970) seems to have the potential for very accurate measurements, but field tests have yet to be made.

3.2 Salinity Gradient Detection

Salinity changes across the Mississippi River outflow were measured by Droppleman et al. (1970) using a passive microwave radiometer operating on 1.4 GHz from a low-flying aircraft. Although this experiment is in its infancy, it is very promising for current boundary detection where changes of 2 $^{0}/00$ may occur over several kilometers. It may prove especially valuable in the region of the ocean between 30°N and 30°S (about half the earth's surface), where surface thermal fronts are absent or seasonal.

The inclusion of a passive microwave radiometer on an oceanographic satellite is most desirable for applications in ice detection and sea state; one channel should operate on 1 to 1.5 GHz. The ground spot size and attitude control requirements discussed for temperature apply to the salinity discussion as well as the other observations discussed below.

3.3 Turbidity Gradient Detection

Clarke et al. (1969) showed that the differences in color of oceanic water masses could be detected from aircraft. These measurements have been linked to the chlorophyll content of the water and hence to its bioassay. Color change between water masses is independent of location, and thus is as valuable in the tropics as in midlatitude regions. The measurements of Clarke et al. (1969) suggest that two narrow (0.015 μ) channels centered on 0.54 and 0.46 μ are necessary to perform these studies. Absolute accuracies needed correspond to the capability of measuring chlorophyll-A concentrations of about 0.2 mg m^{-3} to precisions of ±0.1 mg m^{-3}. This translates (Ramsey, 1968), to an accuracy of 3.0 W m^{-2} $ster^{-1}$ μm^{-1} and a precision of ±1.5 W m^{-2} $ster^{-1}$ μm^{-1}.

3.4 High Velocity Gradients

The other features listed above are covered in sections 2.4 and 2.5 and come naturally out of those requirements, except for item (4), Velocity Gradients. McManus et al. (1968) have shown that a Doppler laser can give absolute current speeds. The adaptability of such a device enables an oceanographer to separate the barotropic flow from the baroclinic flow and, hence, obtain the entire current field from measurement of sea surface slope by an altimeter.

3.5 Other Applications

Being able to measure the thermal, salinity, and turbidity gradients in the open ocean to the required accuracies allows one to easily apply the techniques to esturine and near-shore circulation problems. These areas are of immediate interest in problems of ocean waste disposal, pollution, and recreation. These capabilities also help geological interests solve such problems as longshore transport, and river plume sedimentation.

3.6 Platform Location and Interrogation

Finally, the basic need for Lagrangian drifters in ocean circulation studies must be promulgated. An oceanographic satellite system must be able to locate free drifting buoys and to telemeter basic measurements. Thus the system can also service moored buoys, which serve as operational ground truth stations for the remote measurements. Without periodically comparing remotely sensed data with acceptable standards, we will not have the beginning of genuinely reliable synoptic oceanography.

3.7 Development Studies

Many of the items discussed in this section require further R&D before we attempt to integrate them into a satellite. We strongly recommended that a vigorous aircraft program be supported to determine, first, the optimum spectral bands needed for ocean sensing in order to simplify the satellite as much as possible, and second, to determine if these optimum bands can see through the atmosphere with adequate resolution to warrant integration at all.

4. SURFACE WIND AND WAVE CONDITIONS

Duncan Ross

4.1 Problems

The problem area here is in the general knowledge of surface wind and wave conditions as input to research programs studying the exchanges of heat, energy, and moisture at the sea-air interface. This study will also help the continued development of numerical forecasting of oceanic wind and wave conditions.

There are numerous organizations and programs that desire synoptic wind and wave observations over the oceans. These needs are documented in various reports of the World Meteorology Organization (WMO), World Weather Watch (WWW), etc.

Typical of these are the objectives stated by the WMO in Resolution 1721 (XVI) adopted at the United Nations General Assembly in December 1961:

"1. To develop a deeper understanding of the global circulations of the atmosphere and the associated system of climates;
2. To place weather forecasting on a firmer scientific basis: to develop techniques for predictions on extended time scales and to provide knowledge needed to improve weather forecasts of small space-scales and time space;
3. To explore the extent to which weather and climate may be modified through artificial means."

These objectives have been addressed by numerous organizations, and current experimental programs gather data from ships, aircraft, and satellites. The system requirements stated here will provide additional input to these programs. Section 4 is concerned with the rationale behind the stated requirements; however, note that elements of those requirements are in the area of technology development.

4.2 Requirements

A multi-frequency scanning microwave radiometer system is needed to provide data from which the aforementioned parameters can be inferred. The system should contain the following features:

1. Frequencies - approximately 1-3, 5-8, 10, and 15-19 GHz
2. Polarization - dual
3. Spatial resolution - 20-100 km
4. Scan - ±30-50° orthoganal to ground track and conical at 50°
5. Accuracy - antenna temperatures ±1°K.

We desire to remotely determine oceanic surface wind and wave conditions. Microwave sensitivity to these parameters also appears to be frequency dependent (Hollinger, 1971). Although the mechanism of this sensitivity and its relationship to surface wind and wave conditions are not well understood or quantified, for the sake or argument, we assume our current knowledge is adequate. It remains then to account for the atmosphere at some frequency where adequate sensitivity to sea state is evident.

The proposed approach – a multi-frequency, dual-polarization, passive microwave sensing system – is suggested for the following reasons:

1. By using currently available HRIR images, we can make assumptions about the atmosphere, and good sea state information can be obtained at the higher frequencies (10 and 19 GHz) during clear sky conditions.
2. By using visual and HRIR images to reveal moderate to heavy cloud conditions, we could use 1 or 10 GHz data with the attendant sacrifice in resolution and sensitivity.
3. By using a conical scan at, say, 37 GHz, and with dual polarization at an incidence angle of 50°, we might determine atmospheric moisture content well enough to correct measurements at 19.5 or 10 GHz in order to extend the available sea state "look" opportunities at these frequencies.

The above rationale is, of necessity, somewhat less positive than would be desired, since experimental data now available are sparse. Hopefully, current NASA Goddard Space Center (GSFC), Manned Spacecraft Center (MSC), Langley Research Center (LRC), and planned (NOAA/NRL) experimental programs will yield the desired information. Note that the oft quoted 50-km resolution for sea state determination is based on average conditions. Under the influence of a large extra-tropical storm, reasonably homogenous surface conditions usually extend over several hundred kilometers. Thus, while the availability of 50-km resolution is very appealing, it should not be the only consideration.

4.3 Intended Use of Data

The Atlantic Oceanographic and Meteorological Laboratories will use these data in connection with specific research objectives such as:

1. The effect of fetch and stability on the growth of ocean surface waves
2. The prediction of surf and of shallow and deep water wave conditions associated with hurricanes and extra tropical storms
3. The prediction of storm surge associated with tropical storms and hurricanes.

The desired data would be useful in both the short- and long-term aspects of the above research objectives.

4.4 Justification

The application of passive microwave techniques to marine meteorology is given excellent treatment by Paris (1969 and 1971). In these publications, numerous calculations have been carried out relating to the microwave signature of the ocean and atmosphere, such as, surface temperature, sea state, salinity, and atmospheric moisture. Hollinger (1971), Ross et al. (1970), and Nordberg et al. (1971) present extensive data on the effects of sea state on the microwave brightness temperature. To summarize the conclusions of these workers and others, it may be stated that no one frequency is ideally suited to observing remotely a specific environmental parameter, since all parameters are frequency dependent in their signature and to varying degrees. Thus 19.5 GHz is very sensitive to sea state, but even more so to atmospheric moisture. By choosing a lower frequency such as in the 1 to 3 GHz range, we find that atmospheric moisture sensitivity essentially disappears. Unfortunately, sea state sensitivity also appears to be greatly reduced, while at the same time salinity becomes important. Figures 3 to 11, from the publications by Paris (1969), do clearly show the frequency dependence of some of these parameters.

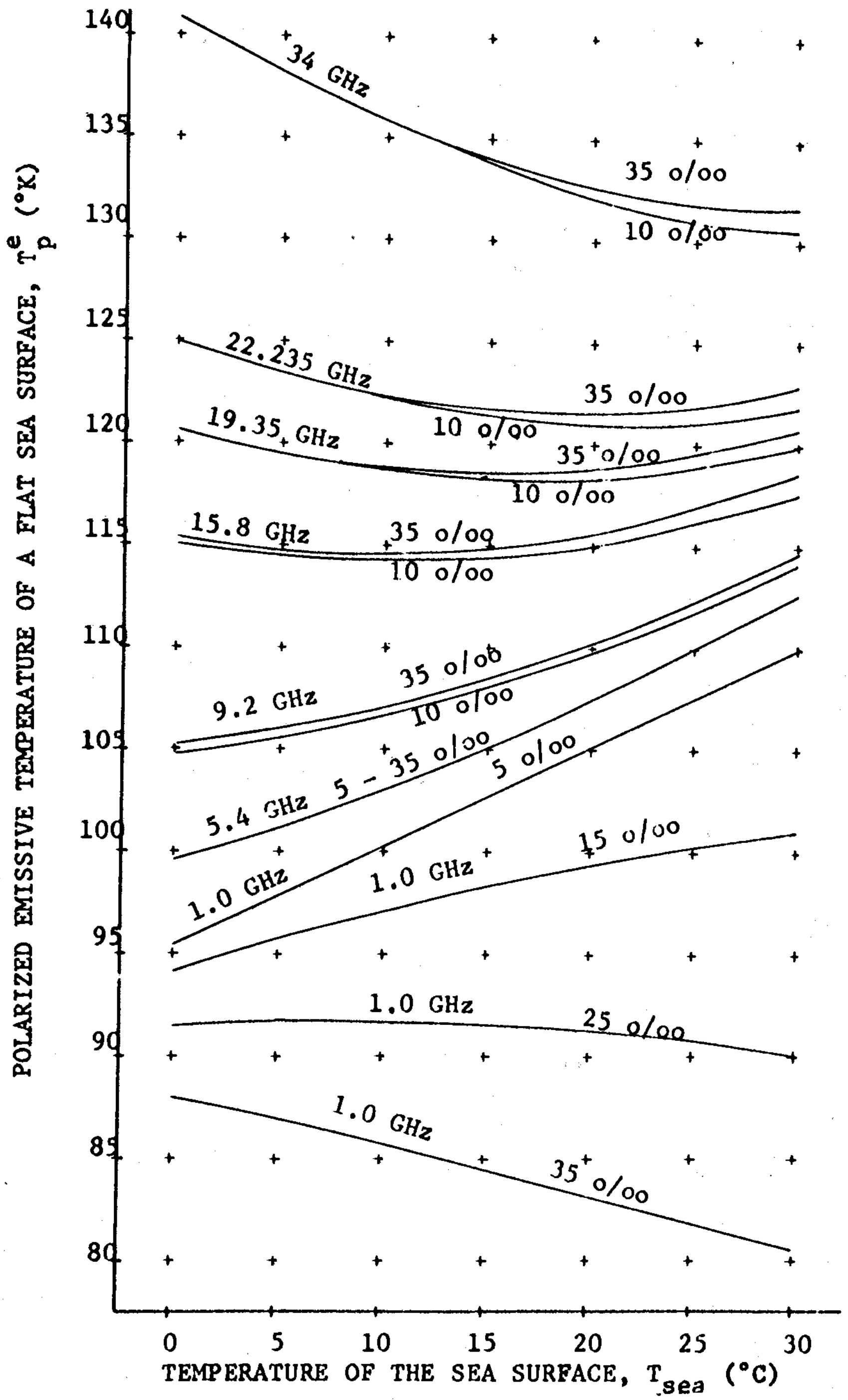

Figure 3. Polarized emissive temperature of a flat sea surface vs. thermometric temperature of the sea surface for 1, 5.4, 9.2, 15.8, 19.35, 22.235, and 34 GHz and for various salinities (Paris, 1969 and 1971).

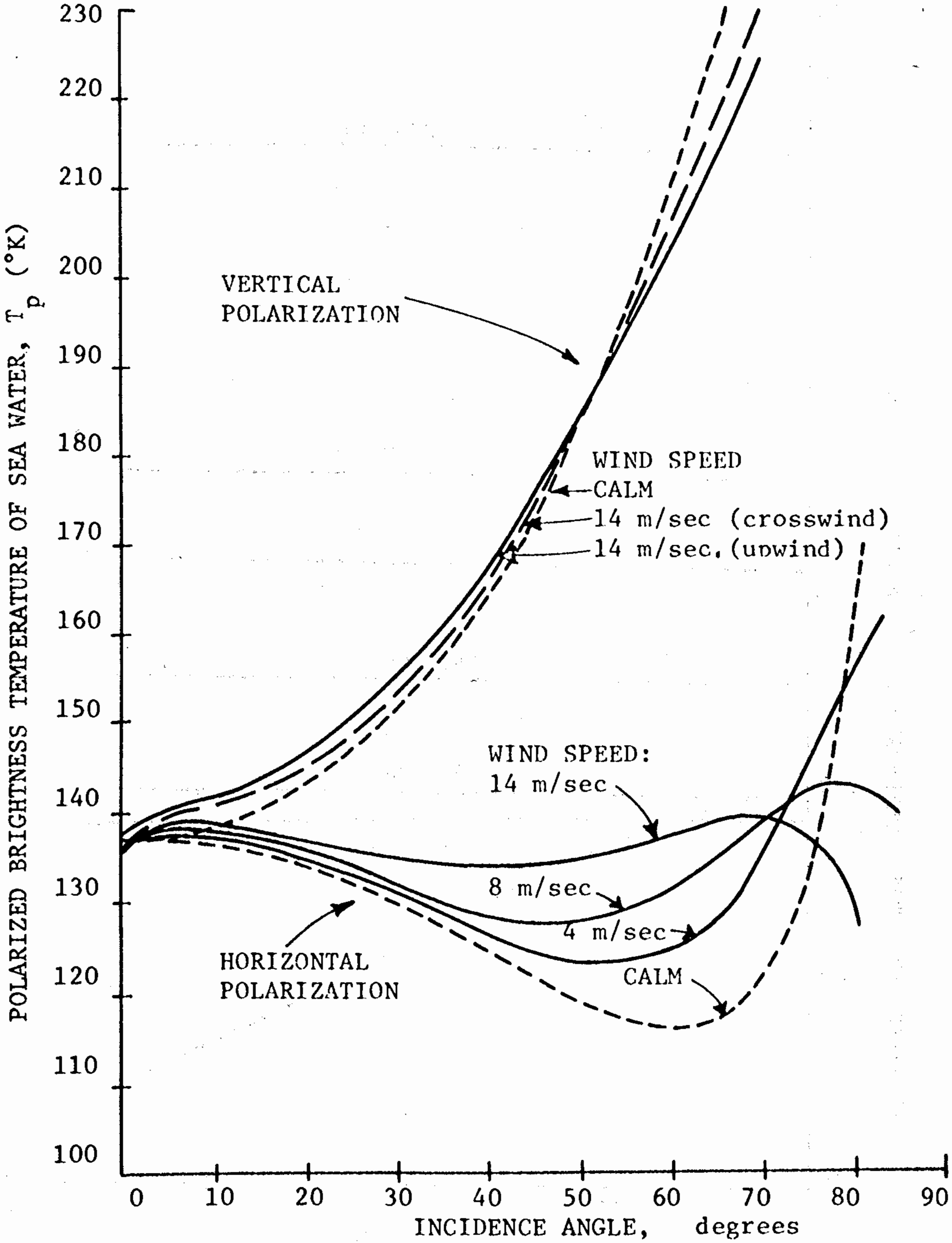

Figure 4. Polarized brightness temperatures of sea water vs. incidence angle for horizontal and vertical polarization, for fully developed sea driven by surface winds of 0, 4, and 14 m/sec; altitude is 1 km, and frequency is 19.4 GHz (from Paris, 1969 and 1971; after Stogryn, 1967).

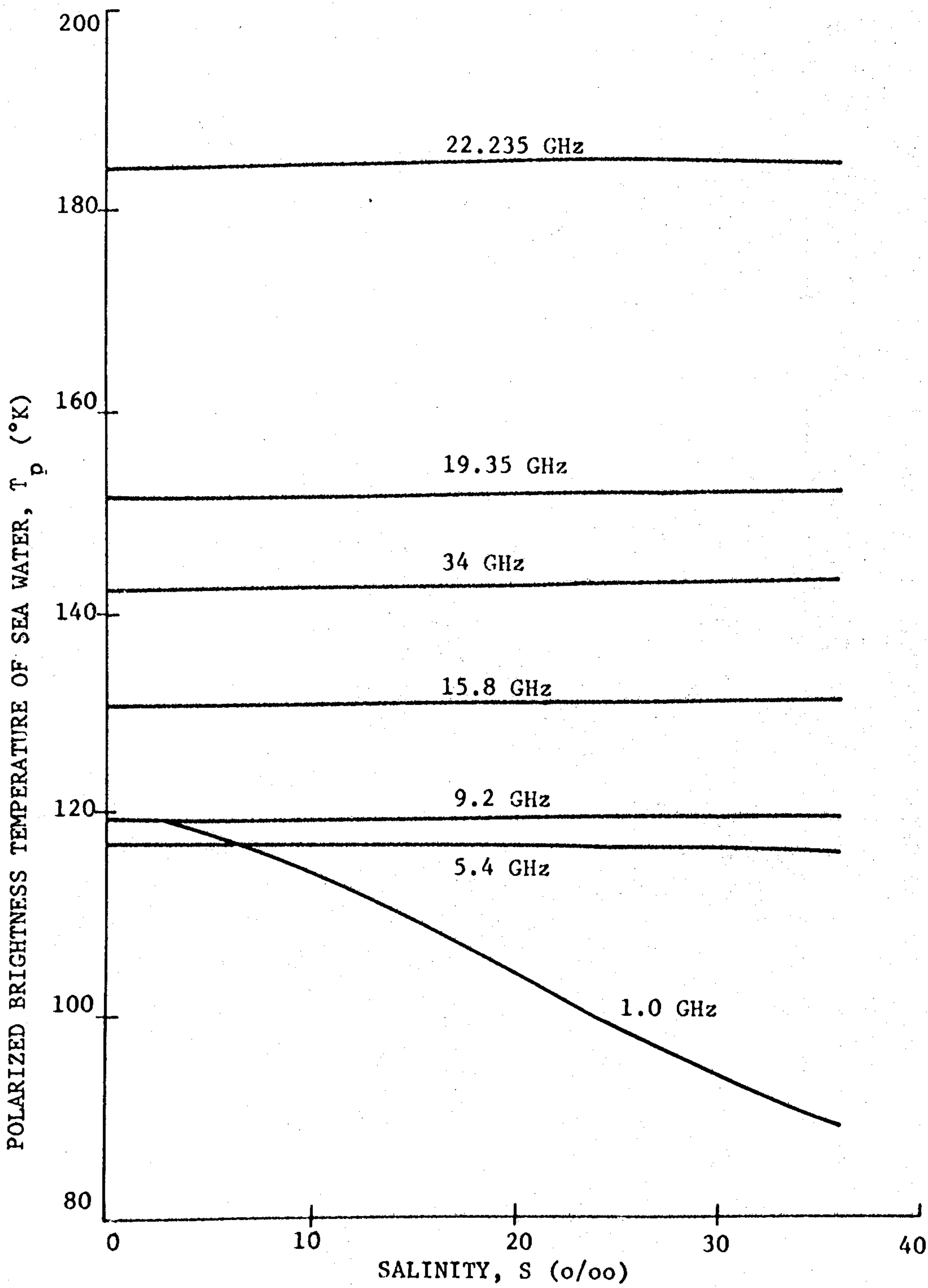

Figure 5. Polarized brightness temperature of sea water vs. salinity for a water temperature of 303°K, an incidence angle of 0°, frequencies of 1, 5.4, 9.2, 15.8, 19.35, 22.235, and 34 GHz, and an altitude of 1 km (Paris, 1969 and 1971).

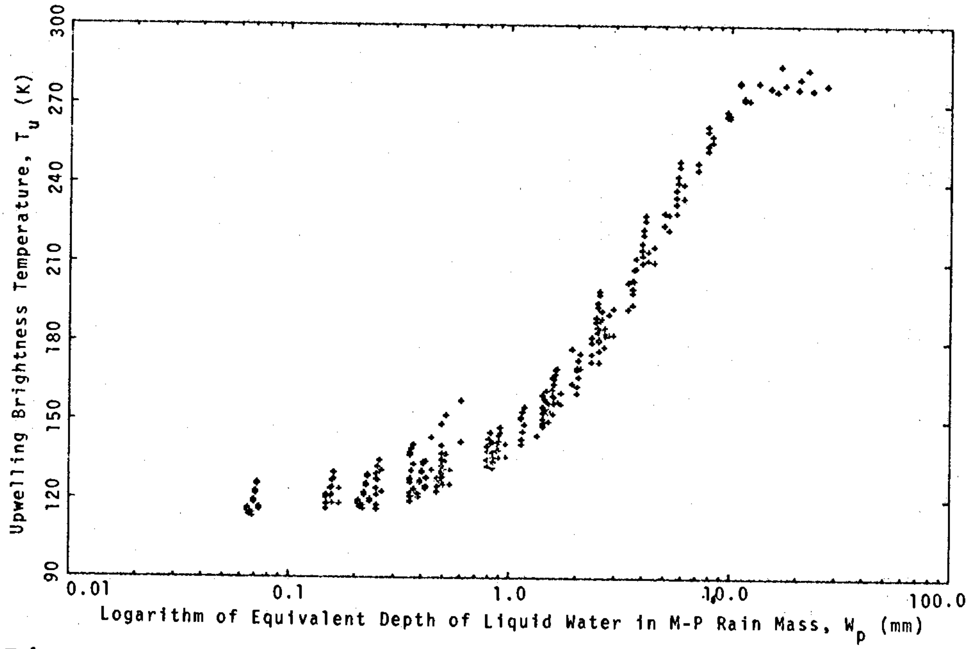

Figure 6. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depths of liquid water in the M-P rain mass: ν = 10.69 GHz (Paris, 1969 and 1971).

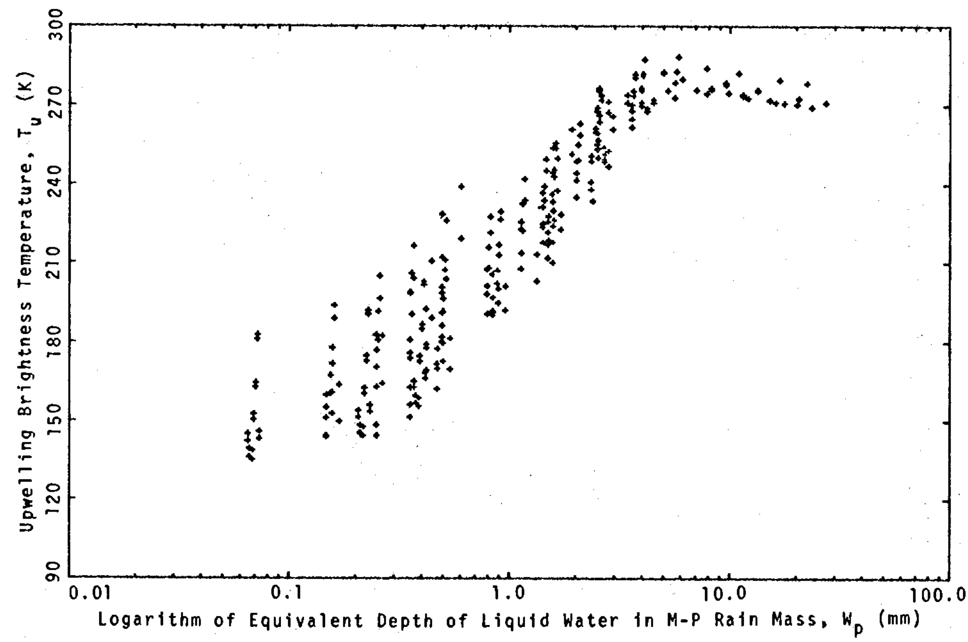

Figure 7. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depths of liquid water in the M-P rain mass: ν = 19.35 GHz (Paris, 1969 and 1971).

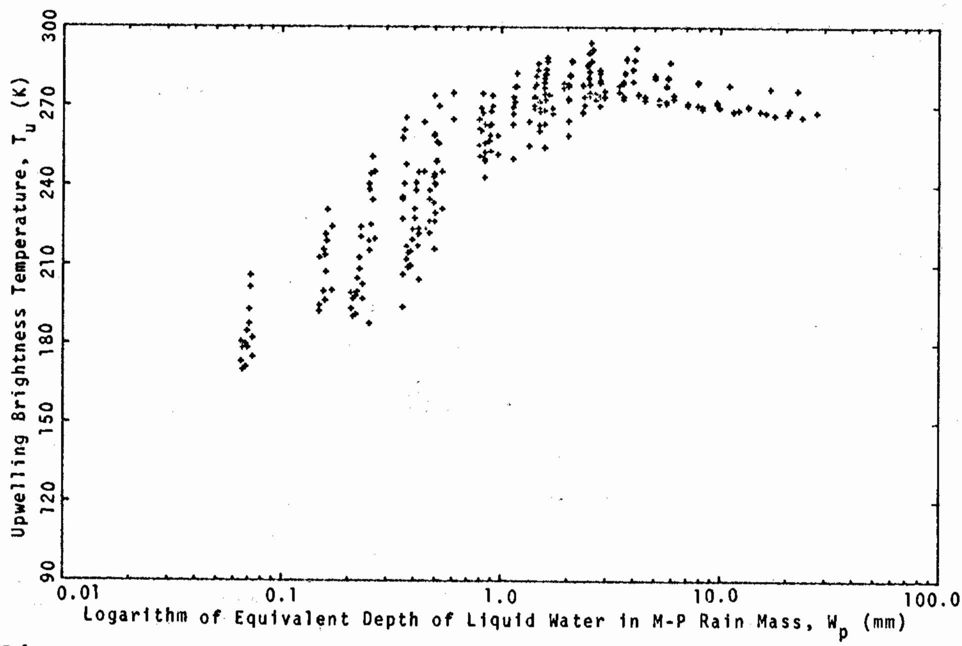

Figure 8. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depths of liquid water in the M-P rain mass: ν = 37.0 GHz (Paris, 1969 and 1971).

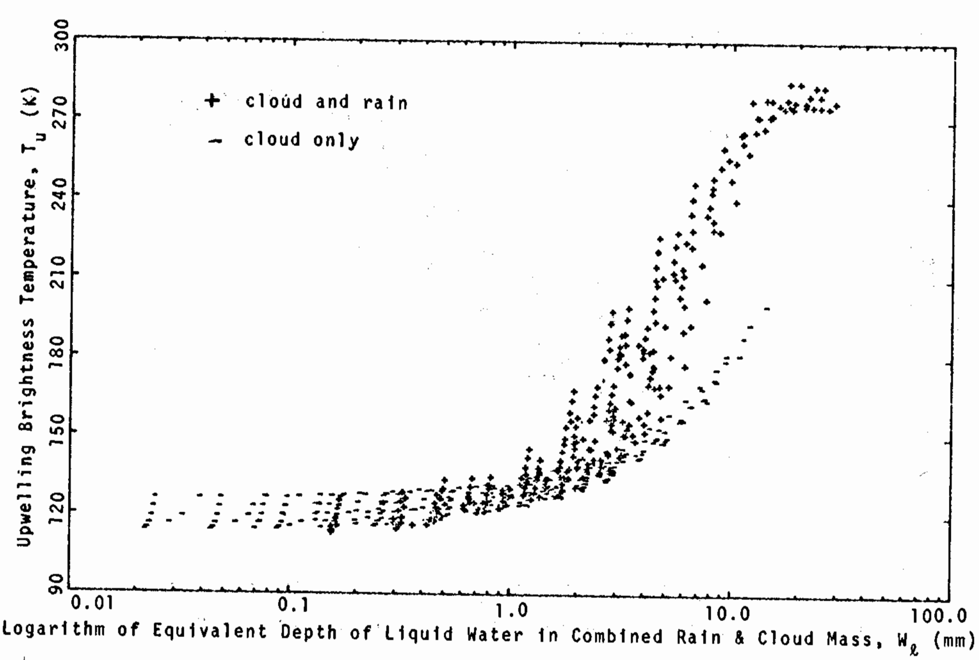

Figure 9. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depth of liquid water in combined rain and cloud mass: ν = 10.69 GHz (Paris, 1969 and 1971).

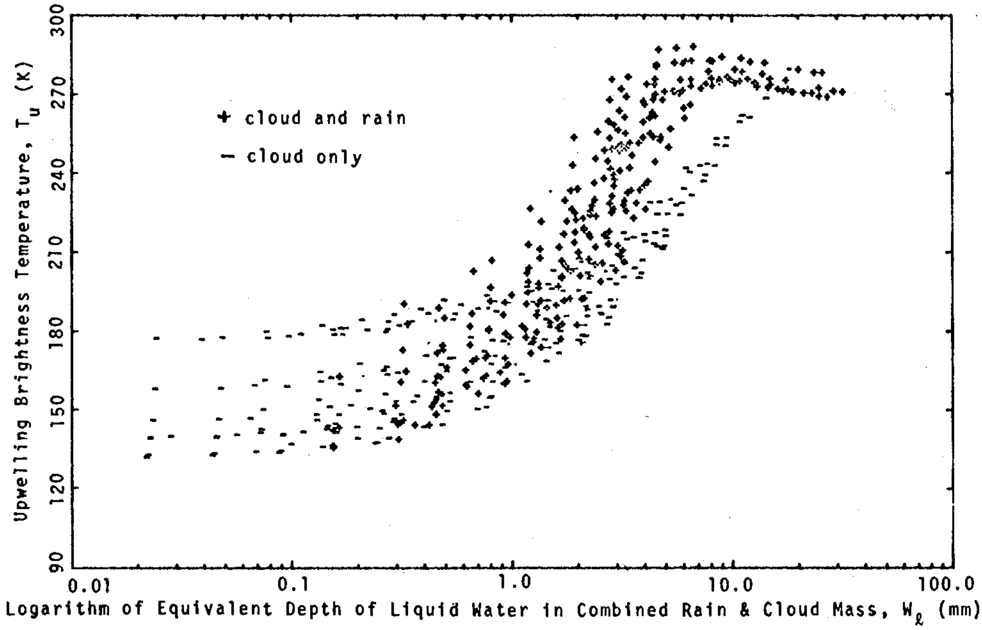

Figure 10. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depth of liquid water in combined rain and cloud mass: ν = 19.35 GHz (Paris, 1969 and 1971).

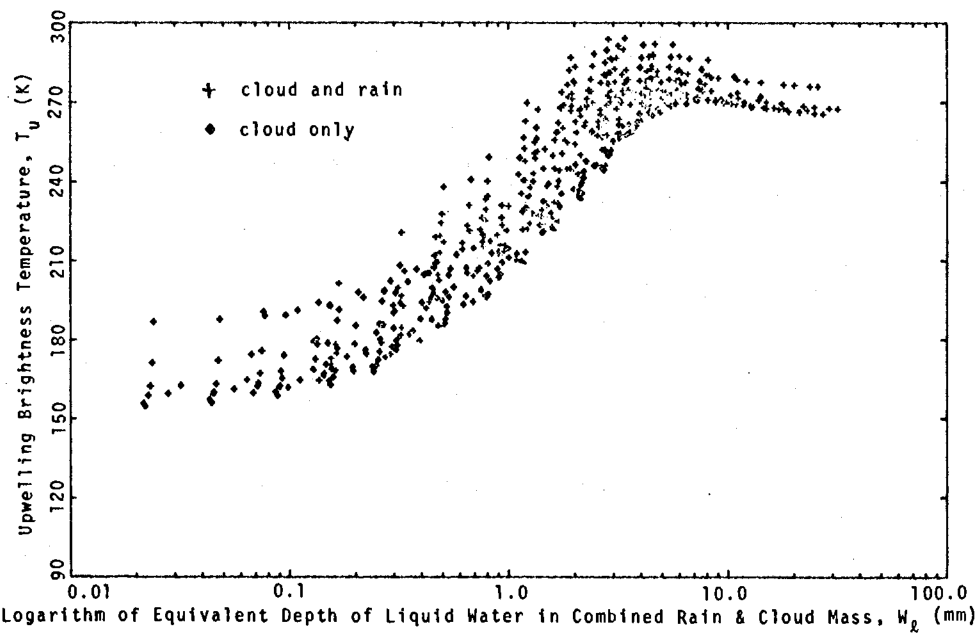

Figure 11. Scattergram of the upwelling radiation of 575 model atmospheres for normal incidence and for a calm ocean vs. their equivalent depth of liquid water in combined rain and cloud mass: ν = 37.0 GHz (Paris, 1969 and 1971).

5. SEA-STATE, TIDES, AND OCEAN SLOPES

John Apel, Bernard Zetler, and Donald Hansen

5.1 Problems

These problems fall into three general categories:

1. Determination of sea state on real-time, synoptic basis, both for research and for monitoring and predicting (NASA Report, 1969).
2. Worldwide determination of tides along coasts and in the midocean, with special emphasis on locating the amphidromic points (Munk et al., 1967; Zetler and Maul, 1971).
3. Measurement of absolute slopes of the sea surface as caused by intense current systems and by deep ocean trenches (NASA Report, 1969).

All three of these problems are, in principle, decipherable by microwave systems on board a spacecraft, e.g., a high precision, short pulse radar altimeter.

5.2 Requirements

1. If the altimeter pulse length is very short — approximately 3 to 10 nsec—the temporal distribution of the returned pulse is a convoluted measure of the distribution of heights of the reflecting surface, i.e., a measure of the state of waves over that part of the sea illuminated by the radar beam (a spot of about 8 km diameter). Recent experiments at NRL (Yaplee et al., 1971) show this technique gives accurate wave spectra for spots that are small compared with an ocean wavelength; in principle, it remains true for large spots, but in an integral form. The research problems are (a) to demonstrate the last assertion experimentally, (b) to develop high power (∿2 kW), short pulse X-band sources that can function in a power-limited satellite, and (c) to devise techniques for sampling the instantaneous signal returned to the satellite at enough points to extract the sea state information from it.

These are difficult technological problems, but ones not insoluable. If handled satisfactorily, the altimeter could form the basis for a multi-satellite, worldwide sea state monitoring and prediction system (Apel, 1971).

2. If the altimeter is also very accurate (atmospheric fluctuations set the minimum altitude error at about 10 cm, while good electronic design can hold the instrument error below that), and if the satellite altitude can be consistently established to a relative precision of about 1 m (larger, constant biases are of no consequence), then ocean tide information with 10 percent error can be calculated by averaging data from a 1° square for a year, provided the tidal amplitudes there are equal to or greater than 1 m (Zetler and Maul, 1971). The technique holds some promise for synoptic studies of tides and a global monitoring and prediction system. It appears, however, considerably more difficult to implement than the sea state monitor. The 5 m precision quoted for current satellites probably could not meet these specifications even if extraordinary efforts are made (Vonbun, 1970). Note that until the sea state problem of item 1 is solved, there is little hope of approaching the required tidal accuracy, because the measured height of the reflecting surface will obviously depend upon the surface roughness as well as its mean elevation.
3. An altimeter having 5 m precision can measure ocean surface slopes such as exist over the deep ocean trenches (15 m depression over 200 km wide). If a 1 m noise figure is achieved, it may also be possible to determine surface slopes (1 m in 100 km) caused by oceanic current systems such as the Gulf Stream or the Kuroshio. It is possible that a combination of laser ranging and short-arc orbit prediction for the satellite would allow single-pass measurements over the Gulf Stream, thereby permitting time-resolved studies of the meanders in that current. The importance of this for a future monitoring and prediction service is apparent.

These three types of oceanographic studies all require a short-pulse, precision altimeter on a vertically stabilized, accurately tracked spacecraft. The orbit should not be synchronized with the major ocean tidal periods and their harmonics (in particular, sun-synchronous orbits are unacceptable);

in addition an inclination of near 65° and a low altitude — approximately 300 to 400 km — permits a view of tides at nearly all latitudes of interest with a minimum radar "footprint" on the ocean surface. With a suitably designed radar altimeter and a significant effort on improved tracking, a mid-1970's satellite could meet the requirements. It is not until the altitude and pulse length figures approach those cited here that a spacecraft with an altimeter becomes seriously interesting for this type of oceanography (Townsend, 1971).

PART II: SOLID EARTH PROGRAMS

6. CHANGES IN SHORELINE AND SEAFLOOR FEATURES CAUSED BY STORMS

George Keller

6.1 Objective

The objective is to determine storm effects on shorelines and shallow water bottom topography in areas of carbonate deposits.

6.2 Problems

Effects of storms (of both minor and major proportions) on the alteration of shorelines and seafloor topography are not yet understood. Photographs taken during space flights indicate that it is feasible not only to record shorelines, but also to record shallow water bottom features (Ross and Jensen, 1969). Several studies have been made on the changes of shorelines by various means, in regard to both long-term changes (e.g., 20 to 40 years) and to rapid alterations resulting from severe storms. Photographic coverage for such studies has not been very complete, e.g., large gaps in the observation intervals. These studies have dealt primarily with shoreline changes and not the adjacent seafloor. The problem we wish to study is the long-term (1 to 2 years) and short-term (1 to 5 days) changes of island shorelines and the surrounding seafloor topography.

This study is proposed for the Bahama Islands, both because of their susceptibility to storm activity and because the clear waters are needed to photograph shallow water bottom features. The more or less continuous photographic coverage obtained by the Earth Resources Technology Satellite (ERTS) systems would provide, for the first time, adequate reference material for a study like this. The correlation of wind and sea velocities and their respective forces with changes in shorelines and bottom topography is the goal of this study.

6.3 Approach

From satellite spectral imagery, the shoreline of a number of islands as well as the size and shape of prominent seafloor features (e.g., sand waves and sand dunes) in the area of the islands will be established. Measuring succeeding images, we can record changes in these features and attempt to correlate these changes with atmospheric and sea conditions. Ground truth measurements will consist of periodic beach surveys on the islands and a sampling program of the bottom features to determine characteristics and variations of sediment texture. Periodically bottom currents will be measured adjacent to the islands to provide additional data on the dynamics of the environment. To obtain greater resolution in photographic coverage of the study area, aircraft photographic surveys will be needed at least twice a year.

6.4 Benefits

The effect of "normal" atmospheric conditions, not to mention severe storms, on shorelines and the characteristics of the adjacent shallow seafloor are poorly known. We expect that the proposed study will provide data that can be used in predicting the effect severe storms will have on shore and near-shore features. Although the study is designed for the Bahamas, it is applicable to the Florida Keys. The study will also serve to evaluate the effectiveness of space observations for this type of problem.

6.5 Requirements

For determining shoreline changes a red spectral band (0.70 μ) is desirable for a clear delineation of the coastline. For determining seafloor changes, greater penetrating spectral bands (0.46 to 0.54 μ) are required for use in water depths up to 30 m. Use of the 0.46 μ and 0.54 μ bands would provide the necessary data.

7. TURBID WATER MASS MOVEMENT

George Keller

7.1 Objective

The objective is to determine the concentration and composition of suspended material in the ocean and to relate this to space photography.

7.2 Problem

Photography taken during space flights has shown that it is feasible to trace turbid water masses seaward from rivers, bays, and coastal lagoons. Although these photographs denote the presence of turbid water, the concentration of suspended material that can be detected is unknown. The problem we wish to pursue is to measure the concentration and composition of the suspended material extending from the Mississippi River into the Gulf of Mexico. We expect to trace the sediment mass and in turn relate this to appropriate photographs taken from space. This will provide the necessary ground control to evaluate the resolution of space photography in regard to turbid water masses. The composition analyses will identify exactly the sediment constituting the turbid mass.

7.3 Approach

Suspended material will be collected at prescribed locations out from the Mississippi River in a series of radial patterns. This will be accomplished by pumping 1 to 100 gallons of sea water from each study site through a series of filters. In addition to the surface waters, samples will be taken from various depths. The amount of organic vs. inorganic matter will be determined as will the composition of the inorganic fraction. A quantitative analysis and identification of the various inorganic constituents will be made by means of X-ray diffraction techniques.

The various concentration values will be compared with satellite photographs of the study area. Additional photography from aircraft (at 5000 ft) is essential to provide added resolution to the study.

The second phase of this study will be observations similar to those mentioned above in the vicinity of Pamlico Sound, North Carolina. Studies by Mairs (1970) clearly revealed that large concentrations of sediment-laden water enter the Atlantic through an inlet in the Hatteras barrier bar. This study, however, did not provide any data on sediment concentration or composition, and thus no ground truth has yet been provided for space photography of these turbid masses. The work will be conducted from NOAA vessels and in the laboratories of the Marine Geology and Geophysics Laboratory of the Atlantic Oceanographic and Meteorological Laboratories.

7.4 Benefits

Limited use has been made of tracing water movement by space photography. The tracing of turbid water masses would provide considerable information on local coastal circulation.

The presence of turbid water appears to correlate very well with the occurrence of marine life, e.g., fish, shrimp. We hope to learn how effective space photography can be for studying the movement of water masses from coastal areas into the sea.

7.5 Requirements

Three spectral bands will be required to delineate the transport of turbid water masses in the coastal zone. The red band (0.7 μ) will detect surface concentrations of turbid masses; whereas, the green (0.46 μ) and blue (0.54 μ) spectral bands will enable the detection of turbid water masses at intermediate depths below the surface. The significance of making color separations in these regions of the spectrum has been discussed by Mairs (1970).

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APPENDIX A

March 31, 1971

Mr. Leonard Jaffe
Deputy Associate Administrator
for Space Science and Applications
National Aeronautics & Space Administration
Washington, D. C.

Dear Len:

The purpose of this letter is to state NOAA's interest in altimetry experiments on proposed NASA satellites such as GEOS-C. We believe these experiments are very important and offer much promise for the future in the field of oceanography and earth sciences.

From our analysis, it is clear that the matter of system accuracy is all important. Accuracies better than one meter will clearly excite the research community and make possible a number of unique and very meaningful experiments such as on ocean tides and dynamics, on ocean surface slopes, and on general sea state monitoring and predicting. If the system accuracy is poorer than one meter, there are still some valuable experiments that could be performed, and one could make use of the data for preparing for more accurate experimentation later on.

Hence, our position is that we urge the highest practical system accuracy. In a crude sense our interest goes up exponentially as system accuracies increase linearly.

Sincerely yours,

John W. Townsend, Jr.
Associate Administrator

bcc: WNHess, Boulder, Colo.
DAJones, Rm 1006, Bldg 1
HBStewart, Miami, Fla.
LWSwanson, Rm 1015, Bldg 1

APPENDIX B

U.S. DEPARTMENT OF COMMERCE
Environmental Science Services Administration
RESEARCH LABORATORIES
Atlantic Oceanographic and
Meteorological Laboratories
901 South Miami Avenue
Miami, Florida 33130

ate: January 5, 1971

ly to of: RF20x5

ject: Status of GEOS-C Radar Altimeter and its use in Oceanography

To: Dr. Harris B. Stewart, Jr.

1. Background

The Geodetic satellite GEOS-C is scheduled for launch late in 1972; on board will be a number of position-determining instruments designed to refine measurements of the geoid to an accuracy of about 5m. These include radar and laser reflectors; doppler navigation; strobe lights; satellite-to-satellite tracking; and an X-band radar altimeter. The latter attracted my attention as a potentially useful tool for oceanography, and B. Zetler and I visited several Washington area laboratories during December 14-18, 1970, to gather further information on it.

The satellite will be in a low inclination orbit ($i=22°$) with its altitude ranging between 700 and 1500km, and will be gravity-gradient stabilized to within 1-2° of the local vertical. Under these conditions it will be observable overhead from the Caribbean and at slant angles from Key West. The radar will be a 3-cm, short pulse ($\tau_\rho \simeq 50$ns) device with a beam width of about 3.5° and an average power of 500W, available something like 50% of the time at best. The designed instrument precision in altitude is 1m rms; the overall system precision is intended to be 5m once the geodetic reference surface is further refined. Note that these numbers are apparently rms errors; there may well exist much larger biases; i.e., the absolute accuracy in position is considerably poorer than the precision, or the repeatability. Indeed, the radar altimeter may be the means by which this bias is reduced.

However, the advertised function of the radar is not to improve accuracy but simply to delineate some of the problems associated with a satellite altimeter; second-or third-generation altimeters based on GEOS-C experience could be expected ultimately to yield a 10-cm precision capability, whereupon the device becomes interesting for accurate measurements of sea surface slopes, tides and the like.

2. Uses of the Radar Altimeter

Even as it stands, the GEOS-C radar may nevertheless provide coarse information on slopes, tides and sea state. As implied in Zetler's memo (Ref. 1), the radar precision is probably too poor to make tidal measurements directly; however, when the radar height measurement is combined with a single, precise satellite range determination - 1.0m obtained from a laser rangefinder and an accurate, short-arc orbit prediction immediately thereafter (valid for track lengths of the order of 100km), it may be possible to observe the following in semiquantitative fashion:

a.) The 15-m depression in sealevel associated with the Puerto Rico trench, which should be readily detectable during a single pass as a local variation in ocean-satellite separation (W. von Arx is pursuing this);

b.) Local sea surface slopes such as arise from western oceanic boundary currents (assuming the satellite track to cross such areas);

c.) With low (or zero) accuracy, deep sea tides.

By looking not at the altitude but instead at the detailed shape of the returned radar pulse in time, the average roughness of the sea surface may be obtained from the distortions which the ocean wave spectrum introduces into this shape. For example, a 10ns pulse occupies some 3m of space along the direction of propagation, and if the variations in the height of the reflecting sea surface are of this order or more, a significant smearing out of the return echo should occur. The research problem is then to discover the quantitative relationships between the actual state of the sea and the broadening of the echo, undoubtedly a project of several years' duration.

Assuming that the information hidden in the pulse can be ultimately deciphered, it is then possible to conceive of a system of several satellites that could provide shipping and weather services with world-wide monitoring of gross average, sea conditions. The data gathered from the altimeters could be processed and digested on the ground and read back into the satellites in a form suitable for relay to ships upon query, so that considerably more information than the instantaneous return under the vehicle would be available. Such a system is in the same spirit as the Satellite Navigation System and indeed its necessity is very nearly spelled out in NOAA's mission statement.

J. R. Apel

Reference 1: "Spacecraft Oceanography Proposal: Tidal measurements (Sampling and Accuracy Problems)", B. Zetler (1970).

GPO 840-711